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2004

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Abstract

This study assessed the temporal and spatial variability in forest growth and carbon storage to provide a comprehensive estimate of the carbon budget for boreal ecosystems in the Lake Abitibi Model Forest (LAMF) in Ontario. In this study, we simulated the stand-level growth and carbon dynamics for the LAMF using a new process-based forest growth and carbon dynamics model, TRIPLEX1.0 (Peng et al. 2002), and GIS (Geographic Information System). The model was recently calibrated and tested using field measurements collected in Ontario (Peng et al. 2002) and from the BOREAS study area in central Canada (Zhou et al. 2003). The model was validated using 49 permanent sample plots (PSP) collected in the LAMF. Simulated breast height tree diameters (DBH) are close to those measured from local PSPs. Simulated carbon storage, that is, net primary productivity (NPP), forest biomass, and soil carbon, were compared with field data and results from other studies for Canada's boreal forests. The results show that the NPP of the LAMF ranged from 3.26 to 3.34 t C ha^{-1} yr^{-1} in the 1990s and was sensitive to changes in annual temperature and precipitation. The NPP values were consistent with values measured during the Boreal Ecosystem-Atmosphere Studies in central Canada. The density of total above- and belowground biomass was 125.3, 111.8, and 106.5 t C ha^{-1} for black spruce, trembling aspen, and jack pine, respectively. The total carbon density of forested land was estimated at 154.4 (t C ha^{-1}) with a ratio of 4:6 for total biomass and soil. Estimates of carbon based on stand variables (tree age, species, soil type, and site class) and analysis of the net carbon balance suggest that the LAMF forest ecosystem was acting as a carbon sink in the 1990s. These results provide information needed by local forest managers to develop ecological and carbon-based indicators and monitor the sustainability of their forest ecosystems.

Acknowledgements

This project was supported by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), the Lake Abitibi Model Forest (LAMF), and partially by the Ontario Ministry of Natural Resources through the Ontario Government Climate Change Fund (TRIPLEX1.0 development). We thank D. Schultz of Abitibi-Consolidated Company of Canada for providing GIS spatial data and useful suggestions, and the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) and J.-N. Candau for providing field data of Boreal Ecosystem-Atmosphere Study (BOREAS) and forest fire. We also thank J.J. Landsberg, H. Bossel, and the CENTURY group for access to their models. Postdoctoral fellowships to X. Zhou and J. Chen through Lakehead University were greatly appreciated. We are also grateful to G. Stanclik (Abitibi-Consolidated) for his assistance with this project.

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Introduction

The boreal forests play a significant role in global carbon cycles and are sensitive to global climate change, particularly temperature and precipitation fluctuations. Under the Kyoto protocol, Canada has committed to reduce its greenhouse gas emission by 6% from the 1990 level by 2010.

Ontario has 69 million hectares of forests, which cover about 65% of Ontario's total land area, and constitute about 17% of Canada's forest land. Since forests can be both carbon sinks and sources, Ontario can play a significant role in national efforts to reduce greenhouse gas emissions. The Canadian General Circulation Model (CGCM) predicts that the expected doubling of atmospheric CO_2 concentration will increase global average air temperature (Boer et al. 1992). In Ontario, temperature and precipitation during the growing season are projected to increase by 10-25% in the northeast but to decrease 10-15% in other parts of the province (Colombo et al. 1998). Forest structure, that is age, growth rates, mortality, and tree species composition, will likely be affected by such changes, and forest ecosystem dynamics will in turn affect climate. An important research area is to understand and predict the effects of climate change on the structure and carbon dynamics of Ontario's forests.

Many studies on simulating boreal forest ecosystems dynamics and carbon budgets have been conducted in the past decade (Running and Gower 1991; Kurz et al. 1992, 1996; Kimmins et al. 1995; Peng et al. 1998; Wang et al. 2001). One well-established national carbon budget model is the CBM-CFS2 (Kurz and Apps 1995, 1996, 1999), which has been used widely for quantifying the effects of disturbances and forest age structure on forest growth and carbon dynamics at both regional and national scales. Peng et al. (2000) used the CBM-CFS2 model to develop a set of carbon-based ecological indicators for Ontario's forest ecosystems since 1920. However, few of the available models consider future environmental changes when predicting future carbon dynamics at landscape levels in Canada. Moreover, most models being used to simulate ecosystem dynamics are designed for describing carbon, soil nutrient, and water cycles. Because they don't take into account the environmental effects on forest growth and yield, they are not used in forest management.

We used the Lake Abitibi Model Forest (LAMF) as a case study to investigate the potential impact of future climate change on forest ecosystems in Ontario. We simulated stand-level growth and carbon dynamics for the LAMF using a new process-based forest growth and carbon dynamic model, TRIPLEX1.0, that was recently calibrated and tested using field measurements collected in Ontario (Peng et al. 2002) and from the BOREAS study area in central Canada (Zhou et al. 2004). The simulation performed at the LAMF included the spatial distribution and dynamics of total biomass, net primary productivity (NPP), soil carbon, and forest growth and yield for the period of 1990 to 2000. Net carbon balance was calculated for 2000.

This study provides a quantitative reference for criteria used for forest management and planning for the LAMF, in particular, for "maintenance and enhancement of forest ecosystem condition and productivity" and "forest ecosystem contributions to global ecological cycles" (Griffin 2001a). Descriptions and analyses of the productivity dynamics and carbon cycle, including the effects of carbon release and harvest at the local level, are provided. Results presented here correspond to most of the indicators required in reporting on criteria of ecosystem productivity and contributions to carbon cycle, such as the dynamics of tree growth, tree biomass, gross primary productivity (GPP), NPP, and soil carbon and water resources.

Methods

Study area description

The LAMF is located in the boreal forest of northeastern Ontario (49°N, 79°W, Figure 1). Its total area (land and water) is 1.2 million ha, of which about 0.9 million ha are forested. The LAMF is one of the 11 forests across Canada that make up the Canadian Model Forest Network, which was initiated by the Canadian Forest Service (CFS) in 1992. The LAMF is composed of two parts: Iroquois Falls North (0.8 million ha of forested area) and Iroquois Falls South (0.1 million ha of forested area) (Figure 1).

The physiography of the LAMF is dominated by the Great Northern Clay Belt (Griffin 2001a). Elevation ranges from 250 to 350 m above sea level. A large area is dominated by glacial outwash and primarily includes fine-textured clay covered by organic deposits in poorly drained areas (Environment Canada 2000, Griffin

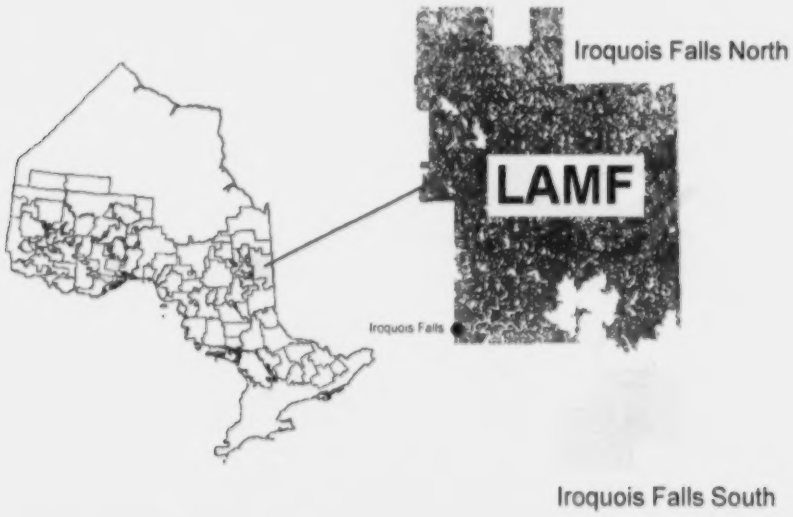

Figure 1. *Location of the Lake Abitibi Model Forest (LAMF) in Ontario.*

2001a). Approximately 50% of the area consists of organic deposits or peatlands with the rest supporting glacial landforms such as eskers, moraines, and drumlins. The climate of the LAMF is influenced by James Bay (Environment Canada 2000) and is characterized by a Humid-Continental climate of short, cool to moderately warm summers and long, cold to severe winters.

Data

Climate

Monthly average temperature, humidity, and precipitation for the LAMF were obtained from the climate database developed by the Canadian Centre for Climate Modelling and Analysis (CCCma 2003). The data cover the period since 1900 and thus meet our needs for simulating old forest stands (> 90 years) in the LAMF, since local climate records are more recent. The climate data are in grid format with cells of 3.75° (longitude) x 3.71° (latitude) for the LAMF area. These data were interpolated for each cell and compared with climate station observations (Price et al. 2001, CCCma 2003).

To simulate carbon in the LAMF forest ecosystem, vapour pressure deficit (VPD) is required as an input variable. In our simulation, the VPD was derived from monthly average precipitation and temperature (Moran and Morgan 1994) as follows:

$$svp = 6.1076*\exp((17.269*T)/(T+237.3)) \quad (1)$$

$$vp = RH*svp/100 \quad (2)$$

$$VPD = svp - vp \quad (3)$$

where svp is saturation vapour pressure (mbar), vp is vapour pressure (mbar), T is average temperature for the month (C°), and RH is relative humidity.

Permanent sample plots

Growth and yield data from permanent sample plots (PSP) were used for assessing forest mortality and validating the TRIPLEX1.0 simulation for stand variables, such as tree heights and diameters. Plot locations with road access are shown in Figure 2; Appendix 1 lists longitude, latitude, and MNR codes for the plots used in this study (OMNR 1996). The PSP database (OMNR 1996) contains time of plot establishment and associated soil information. Dominant tree species are black spruce (*Picea mariana*), jack pine (*Pinus banskiana*), balsam fir (*Abies balsamea*), white birch (*Betula papyrifera*), glossy buckthorn (*Rhamnus frangula*), and trembling aspen (*Populus tremuloides*). Stand age ranged from 9 to 119 years and DBH ranged from 3.1 to 45.0 cm in the sample plots.

Stand information

Overall stand type, forest type, tree age, stocking, site class, tree species, and average tree height information

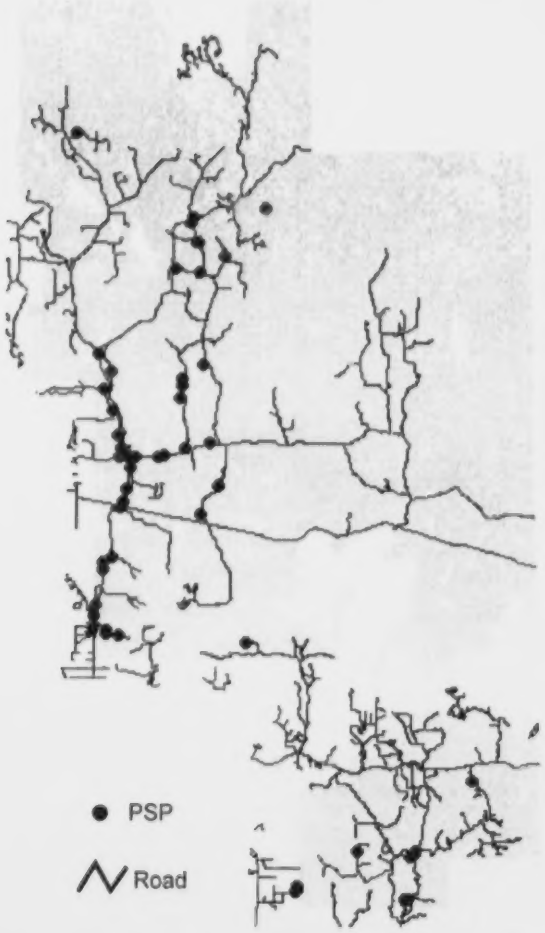

Figure 2. *Location of permanent sample plots (PSP) in the Lake Abitibi Model Forest (LAMF).*

were obtained from LAMF files. Dominant tree species are: trembling aspen, jack pine, black spruce, black ash (*Fraxinus nigra*), balsam fir, cedar (*Thuja occidentalis*), larch (*Larix laricina*), and balsam poplar (*Populus balsamifera*). Trees ranged from 2 to 283 years old in 2000 (Figure 3a). Forests in Iroquois Falls North are generally older than those in Iroquois Falls South. The spatial distribution of tree species and average tree height are shown in Figures 3b and c.

Harvest and regeneration

The current Forest Management Plan for the LAMF covers the period 1995 to 2015 and is reviewed every 5 years. Figures 4a and 4b illustrate the area and volume of harvest in the LAMF from 1985 to 2000. Allowable harvest is approximately 750,000 m^3 annually. This allowable harvest volume was converted from the allowable harvest area (43,350 ha for every 5 years) that was determined by the Forest Management Plan. The trends in harvest (Figure 4b) only reflect the production of primary wood products, such as oriented strand board, pulpwood, saw logs, and veneer. Secondary products were fewer and more difficult to assess. The LAMF practices what is called "best end-use" where residual chips from saw log processing are used in pulp mills, reducing the harvest required to meet mill demands. Regeneration is an important component of sustainable forest management. To ensure the areas that have been harvested are successfully regenerated, regeneration activities are monitored based on prescriptions developed for a specific harvest area (Griffin 2001a). It provides the year regenerated and species information required for the simulation runs.

Forest fire

Observations of forest fire occurrence were obtained from a database constructed by the Ontario Ministry of Natural Resources (OMNR). OMNR digitized data to produce a comprehensive database for all large fires (greater than 2 km^2) that occurred in Ontario between 1921 and 1995 (FLEP 1998, Fleming et al. 2002). Annual fire data are provided in GIS ArcView spatial format.

Soil texture

The soils in the LAMF are primarily fine-textured clays, covered by organic deposits in poorly drained areas (Griffin 2001a). These organic deposits or peatlands cover more than 50% of the LAMF area. A number of glacial landforms, such as eskers, moraines and drumlins, can also be found in this area. The Ontario Land Inventory and Primeland/Site Information System (Elkie et al. 2000) provides details of soils in Ontario's forest ecoregions. Table 1 summarizes the soil composition in the LAMF. Figure 5 shows the distribution of soil textures across the area.

Model description

Model structure

TRIPLEX1.0 is a generic hybrid simulation model that combines the advantages of both empirical and process-based models (Peng et al. 2002). This model was

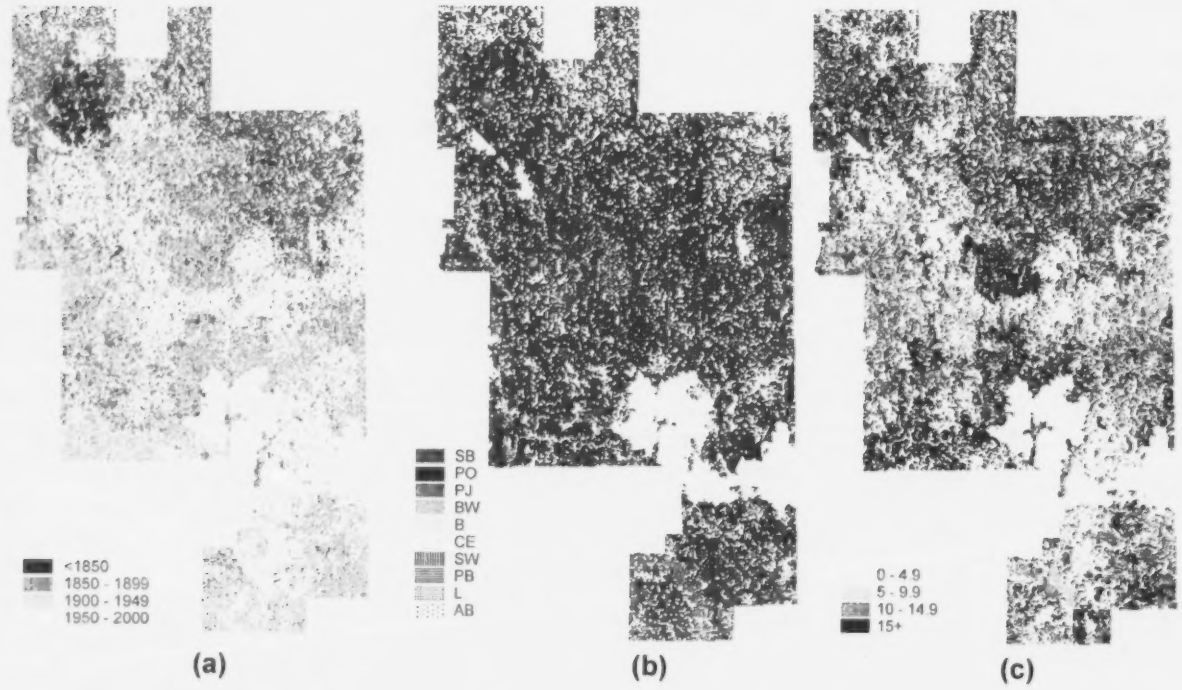

Figure 3. *Spatial distribution of (a) year forests regenerated in the LAMF, (b) tree species (SB, Black spruce; PO, Trembling aspen; PJ, Jack pine; BW, White birch; B, Balsam fir; CE, Cedar; SW, White spruce; PB, Balsam poplar; L, Larch; AB, Black ash), (c) average tree height (m) measured for 1994 in the LAMF.*

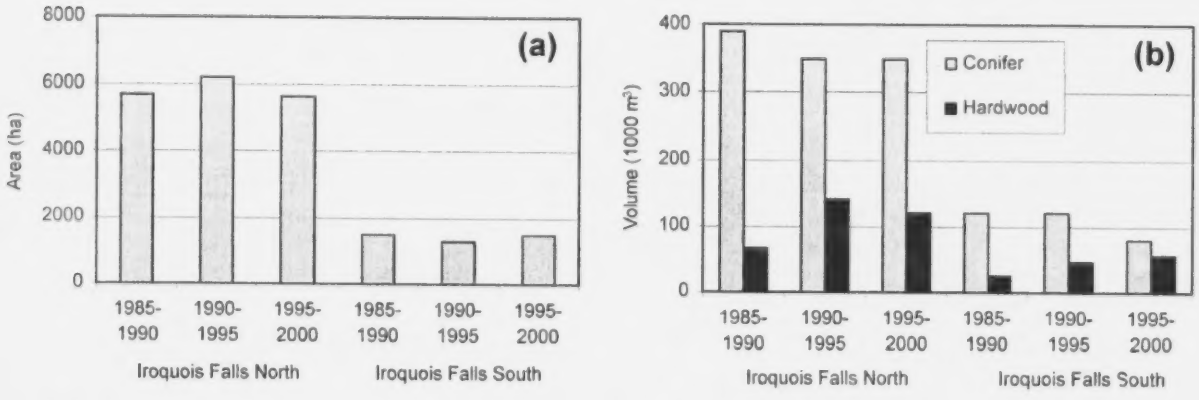

Figure 4. *Actual average annual (a) harvest area and (b) harvest volume in the LAMF.*

Table 1. The relative area of various soil types in the LAMF[a].

Soil texture type	Area (ha)	Proportion
Clay	690,423	65%
Clay and medium sand	26,42	2%
Fine sand	169,099	16%
Medium sand	24,191	2%
Total	1,063,670	100%

[a] These areas include some barren and other non-forested land; lakes and rivers were disregarded.

constructed for bridging the gap between empirical forest growth and yield and process-based carbon balance models. TRIPLEX1.0 includes 4 major components (Figure 6): (1) a forest production submodel that estimates photosynthetically active radiation (PAR), gross primary productivity (GPP), and above- and belowground biomass; (2) a soil carbon and nitrogen submodel that simulates carbon and nitrogen dynamics in litter and soil pools; (3) a forest growth and yield submodel that calculates tree growth and yield variables (e.g., height, diameter, basal area, and volume); and (4) a simple soil water balance submodel that simulates water balance and dynamics. Simulation involves key processes and dynamics including PAR, GPP, forest growth, biomass, soil carbon, soil nitrogen, and soil water. In this study, all simulations were conducted using a monthly time step and outputs were summed annually.

TRIPLEX1.0 is comprehensive without being complex, and minimizes the number of input parameters required. Inputs include the location (latitude), climate, and some initial site conditions. TRIPLEX1.0 had been previously calibrated and validated for pure jack pine stands in Ontario (Peng et al. 2002, Liu et al. 2002) and for major boreal tree species in central Canada (Zhou et al. 2004). The previous comprehensive calibration and independent validation efforts provide a scientifically sound foundation for the further use of TRIPLEX1.0 in the LAMF area.

Sub-models

Here we provide a brief description of the TRIPLEX1.0 model (for details refer to Peng et al. 2002, Liu et al. 2002):

Figure 5. *Distribution of soil texture in the LAMF (CL, clay; FS, fine sand; MS, medium sand; CM, clay and medium sand; NC, unclassified).*

1) *Forest production sub-model.* This sub-model consists of photosynthetically active radiation (PAR), GPP, and carbon allocation modules. PAR was calculated as a function of solar constant, radiation fraction, solar height, and atmospheric absorption. Initial PAR was estimated as a solar constant (1360 Wm^{-2}) with the solar radiation fraction set as 0.47 (Bossel 1996). Solar height is calculated based on site latitude and time of day. GPP was calculated monthly based on received PAR, forest age, monthly mean air temperature, vapour pressure deficit, soil drought, and percentage of frost days in the month. Ryan et al. (1997) suggested a fixed fraction (C_{NPP}=0.39) that we used for estimating the proportion of NPP in GPP for boreal forest ecosystems. Carbon allocation was defined depending on the apportioning of carbon assimilation among the foliage, stem, and root.

2) *Forest growth and yield sub-model.* Individual tree height and diameter increments are calculated from stem wood mass increment. Annual increments of

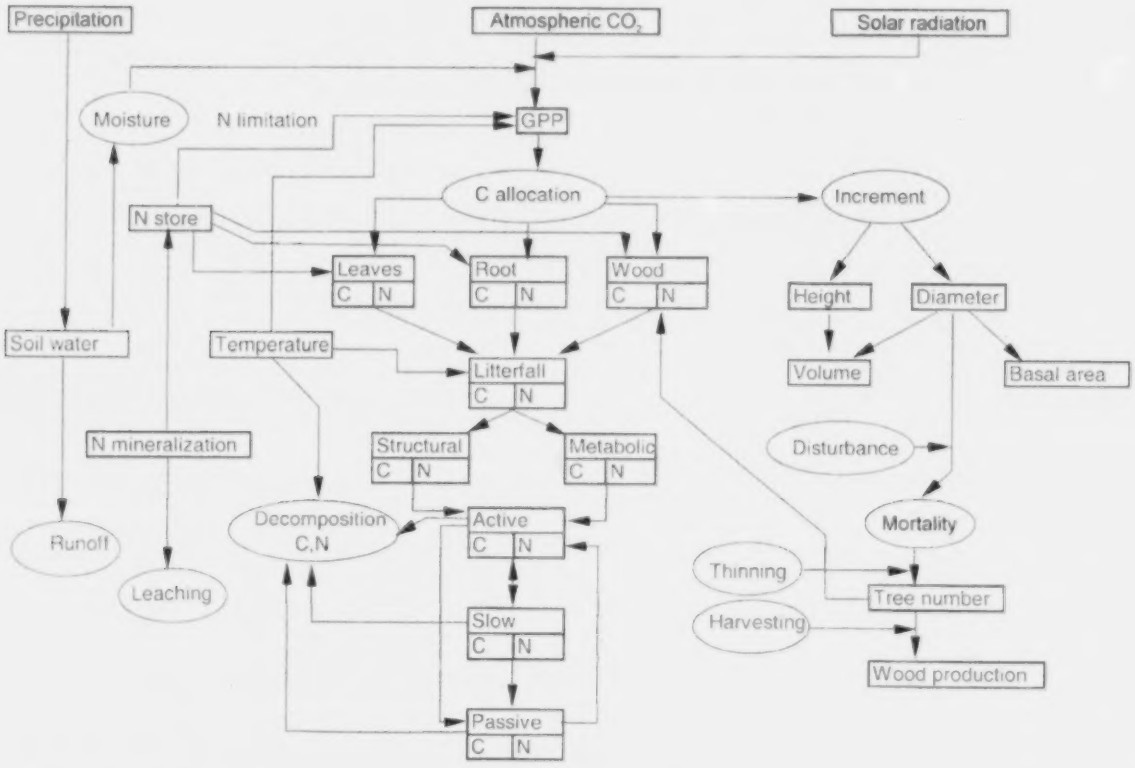

Figure 6. *Structure of TRIPLEX1.0 model (from Peng et al. 2002).*

individual tree height are calculated as a function of stem wood biomass increment, tree diameter at breast height, height/diameter ratio, wood density, and tree form factor. Height and diameter growth are influenced by a combination of physiological and morphological responses to environmental factors. Height to diameter ratio has been proposed as an alternative competition index to be used in determining the free growth status of the tree. We used the assumptions proposed by Bossel (1996) to calculate tree height and DBH growth. These are (a) if crown competition is occurring, trees grow more in height; (b) without crown competition, trees grow more in diameter; and (c) carbon mass of an individual tree is estimated as a product of tree volume and the specific wood carbon density.

3) *Soil carbon and nitrogen sub-model.* This is based on CENTURY's soil decomposition sub-model (Parton et al. 1993). It provides estimates of both carbon and nitrogen mineralization rates for Canadian boreal forest ecosystems (Peng et al. 1998). The rate of soil carbon decomposition for each pool was calculated as a function of carbon stock for a particular pool, maximum decomposition rate, and effects of soil moisture and temperature.

4) *Soil water balance sub-model.* This component incorporates the soil water sub-model of CENTURY. It is a simplified water budget model that calculates monthly water loss through transpiration, evaporation, water content of soil, and snow water content. Water inputs are rainfall including snow; outputs are transpiration, evaporation, and leached water.

Downscaling

The climate data used in this study were generated using GCM and have the following inherent problems: (1) the model mesh is too coarse to resolve the finer features of a forest ecosystem that is sensitive to local climate; (2) the values of the climate state variables at the grid points, at least at the centre points of each stand, must be known to represent the state for the entire stand. In this study, a downscaling technique introduced by Oelschlagel (1995) was used to interpolate climate values. It interpolates all the climatic

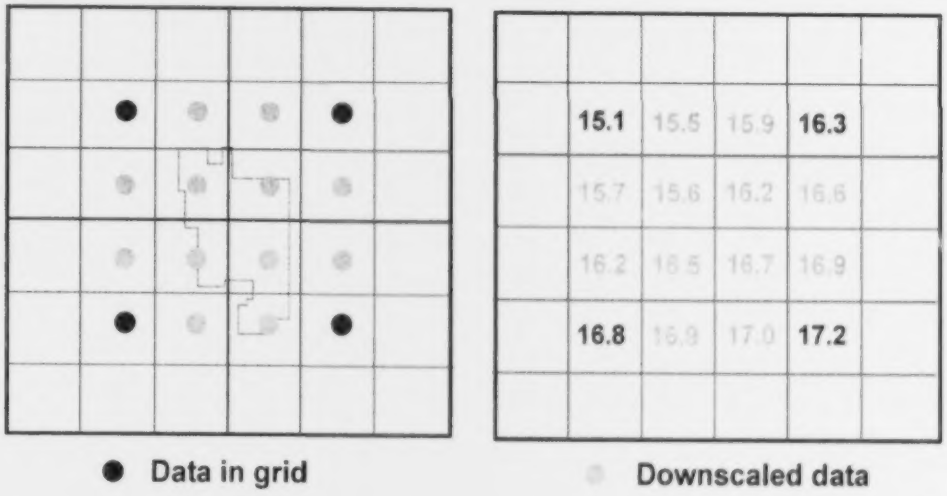

Figure 7. *Grids and points used in the computations, showing downscaling mode.*

variables needed by TRIPLEX1.0 from large scales. Figure 7 illustrates the downscale algorithm, which can be described as follows: To downscale, only the 4 nearest grid points around the target location (LAMF) were used. Twelve interpolated points are generated from the 4 original points. For air temperature and precipitation, monthly averages at every grid point were interpolated and the result was added to the averages in the target location. Interpolation was used for centroid points of each polygon (forest stand) but not all grid points. We assumed that the value at the centroid represents the climate of the entire stand regardless of its shape (e.g., gray shape in Figure 8).

Simulations

The simulated variables include carbon balance, net primary productivity (NPP), above- and belowground biomass, soil carbon, and forest growth variables. The carbon balance was calculated as:

Net carbon balance (NCB) = NPP – carbon release

Net biome productivity (NBP) = NCB – carbon loss by harvesting

where carbon release includes carbon emission by plant respiration and soil decomposition.

Forest biomass is an accumulation of NPP over years with litter fall decomposing and adding carbon to soil. Annual harvest removes forest biomass from the ecosystem and decreases carbon stocks. Most parameters for TRIPLEX1.0 were adopted from our earlier results (Zhou et al. 2004); however, the following parameters were specifically determined for the LAMF simulation by analyzing local and published data:

- Mortality. Two mortality parameters (normal mortality ratio and crowding mortality ratio) are used in TRIPLEX1.0 for calculating dead trees with crowding competition. Normal mortality ratio estimates based on the literature ranged from 0.002 – 0.01 monthly where the tree density is less than 6000 trees ha^{-1} (Plonski 1974, Bossel 1996, Mitchell 2000). In this study, normal mortality ratio was set as 0.006 $month^{-1}$; the crowding mortality ratio was determined to be 0.02 (Bossel 1996).

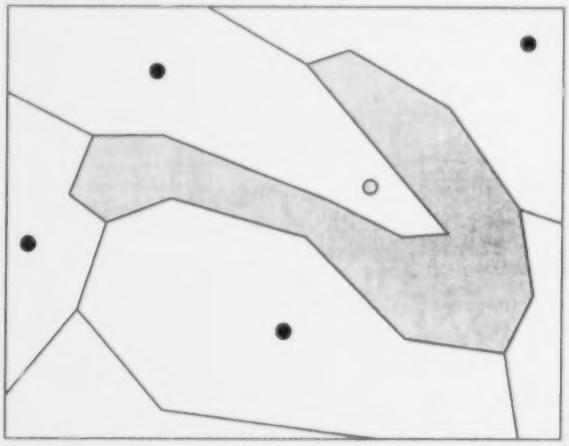

Figure 8. *An example showing location of centroid points in various forest stand types for downscaling climate data.*

Table 2. Estimated average forest yield statistics for the LAMF for 2000 showing regional differences.

	Iroquis Falls North	Iroquis Falls South	Average
Tree height (m)	13.1	13.3	13.1
DBH (cm)	11.2	10.0	11.1
Basal area (m^2 ha^{-1})	27.1	25.2	26.8
Volume (m^3 ha^{-1})	176	162	174
Total volume (M m^3)	136	21	-

Table 3. The status of forest growth in the LAMF for 2000 showing species differences.

	Black spruce	Jack pine	Aspen	Others
Tree height (m)	11.3	17.1	20.0	15.6
DBH (cm)	10.9	9.7	12.8	9.7
Basal area (m^2 ha^{-1})	27.3	29.9	23.1	25.2
Volume (m^3 ha^{-1})	158	282	184	252
Total volume (M m^3)	107	11	21	18

- Wood carbon density. Wood carbon densities for different tree species have been summarized in a number of studies (Alemdag 1984, Dixon et al. 1991, Dewar and Cannell 1992, Schroeder 1992, Nabuurs and Mohren 1995). In this study, the wood carbon density (carbon weight per fresh volume) was calculated from the Global Forest Practices Database (Mitchell 2000), which provides average values for individual boreal tree species measured in Canada, Finland, Russia, and Sweden. The average wood carbon density was estimated to be 0.23 t C m^{-3} for black spruce, 0.22 t C m^{-3} for jack pine, and 0.19 t C m^{-3} for trembling aspen.

Results and Discussion

Forest growth

Simulated tree height, DBH, basal area, and volume for the year 2000 are given in Tables 2 and 3. Their spatial distributions are presented in Figure 9. Average volume density simulated for the LAMF (about 163 m^3 ha^{-1}) agrees with the results of the Canada's Forest Inventory for the region (Gray 1995). Simulated tree height also corresponds with field measurements (Figure 10) with coefficients of determination (r^2) of 0.89, 0.73, and 0.85 for black spruce, jack pine, and trembling aspen, respectively. In this study, individual

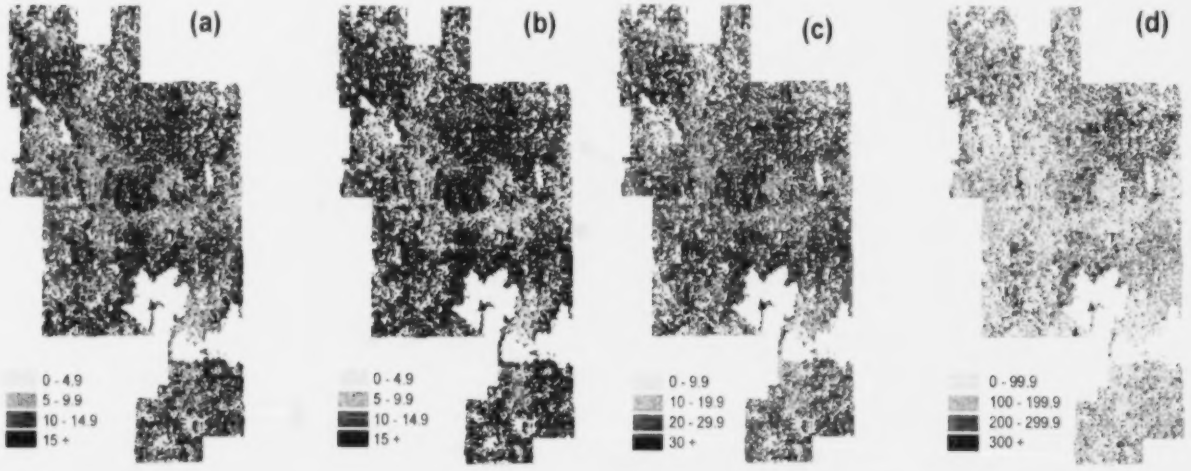

Figure 9. Status of growth and yield simulated for 2000 in the LAMF, a - tree height (m); b - DBH (cm); c - basal area (m^2 ha^{-1}); d - volume (m^3 ha^{-1}).

tree height and diameter increments are calculated from biomass (stem wood mass) increment rather than using empirical growth functions. In this way, the model has better long-term forecasting ability within changing environments including climate, soil, and water conditions. The higher r^2 implies that the volume derived from tree height and DBH can be considered less biased and the results validate the use of the simulation model in the LAMF.

Biomass distribution

The distribution of biomass density was somewhat related to tree age distribution. Soil type, stand nutrition condition, and site class also contributed to the accumulation rate of biomass. The biomass density in Iroquois Falls North is higher because trees are older (see Figure 11). Iroquois Falls North supports 89% of the total wood biomass, whereas Iroquois Falls South had only about 11% of the biomass. Figures 12 and 13 present an analysis of the biomass distribution by age class. Four main tree species groups occur in the LAMF (Table 4) with "other" referring to black ash, white birch, cedar, larch, balsam poplar, and white spruce. Black spruce had the highest percentage (78%) of aboveground biomass and jack pine had the lowest (4%), aspen and "other" were 11% and 7%, respectively. The total biomass was mainly distributed within age classes ranging from 70 to 150 years (Figure 13), which contained about 69% of the total forest biomass in the LAMF in 2000. Protected forest was less than 0.1% of total biomass in the LAMF in 2000.

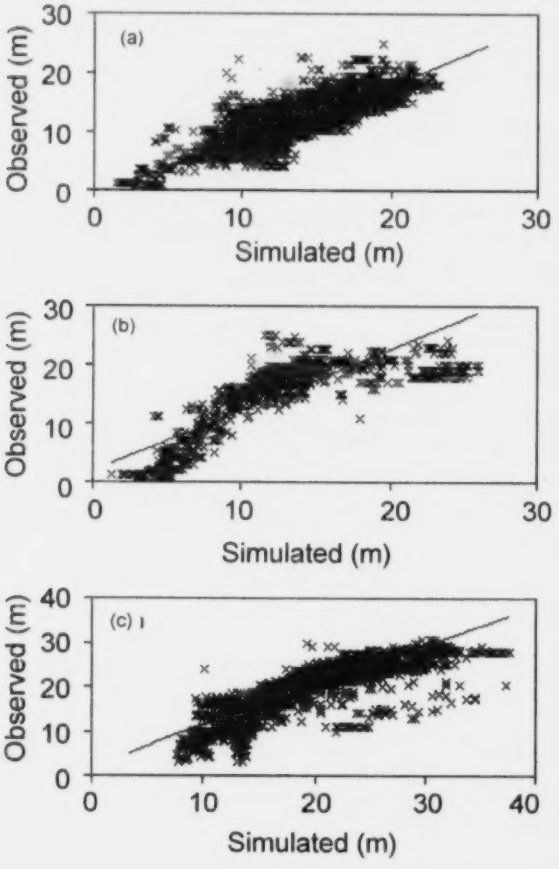

Figure 10. *Comparisons between simulated and observed on tree height for (a) black spruce (n=33,173, r^2=0.89, slope=0.94, intercept=-0.55), (b) jack pine (n=1,831, r^2=0.73, slope=1.03, intercept=-1.85), and (c) trembling aspen (n=5,978, r^2=0.85, slope=0.89, intercept=2.53).*

The dynamics of belowground biomass were also simulated, including coarse and fine roots. Coarse roots were those greater than 5 mm and fine roots were less than or equal to 5 mm (Ryan et al. 1997). Belowground biomass distribution was similar to that of aboveground biomass. Some differences were apparent among sites, with more belowground biomass on areas with lower site class (Table 5). Biomass was highest in stands on Site Class 2 areas, which supported 60.5 Mt and 54% of total biomass in 2000 (see Table 6). Site Class 1 and 2 represents about 87% of total biomass in the LAMF. Figure 14 gives the spatial distribution of site classes in the LAMF. Biomass distribution changed somewhat every year because of harvesting. However, less harvesting (Figure 4) has not affected the overall biomass distribution across the LAMF. Forest fires occurred only in 1997 and total burn area covered only 0.38% of the total LAMF area, and thus did not affect biomass dynamics. As the total amount of forest growth was greater than that lost to disturbance (harvested and burned), total biomass in the LAMF increased slightly from 1990 to 2000 (Figure 15). The rate of total biomass increase was higher in Iroquois Falls South (9.7%) than North (6.9%), likely because most stands were younger and the climate conditions were better in Iroquois Falls South. In this study, understory biomass was not calculated independently since it amounts to less than 1% of total biomass, estimated based on data from Gower et al. (1997).

When estimating annual biomass increment, determining NPP allocation for the stem, root, and leaf is an important step in the simulation process.

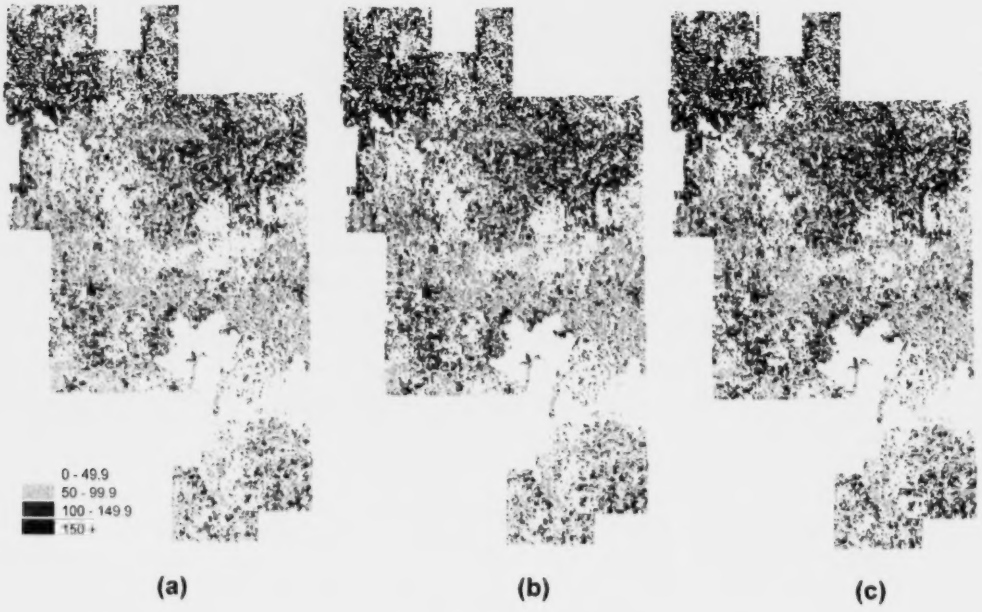

Figure 11. *Distribution of biomass density (t C ha^{-1}) in the LAMF for (a) 1990, (b) 1995, and (c) 2000; includes above- and belowground biomass.*

Table 4. *Aboveground biomass by tree species in the LAMF estimated for 2000.*

Tree species	Total aboveground biomass (Mt)	Average (t ha^{-1})
Black spruce		
north	60.4	96.2
south	5.6	85.9
Sum (percentage of total)	65.9 (78%)	
Aspen		
north	7.9	90.0
south	1.6	65.7
Sum (percentage of total)	9.5 (11%)	
Jack Pine		
north	2.3	83.6
south	0.9	73.0
Sum (percentage of total)	3.1 (4%)	
Overall		
north	74.8	94.1
south	9.5	78.3
Sum (percentage of total)	84.3 (100%)	91.9

Table 5. *Proportion of belowground biomass relative to total biomass by site class in the LAMF estimated for 2000.*

Site class	Belowground biomass (% of total)
1	24.0%
2	24.3%
3	25.3%
4	29.5%
Average	24.4%

Table 6. *Total and average biomass, including above- and belowground, by site class in the LAMF estimated for 2000.*

Site class	Biomass density (t ha^{-1})	Total biomass (Mt)	Percentage
1	129.6	36.2	33%
2	128.8	60.5	54%
3	92.8	12.3	11%
4	71.9	2.1	2%
Average or Sum	120.9	111.0	100%

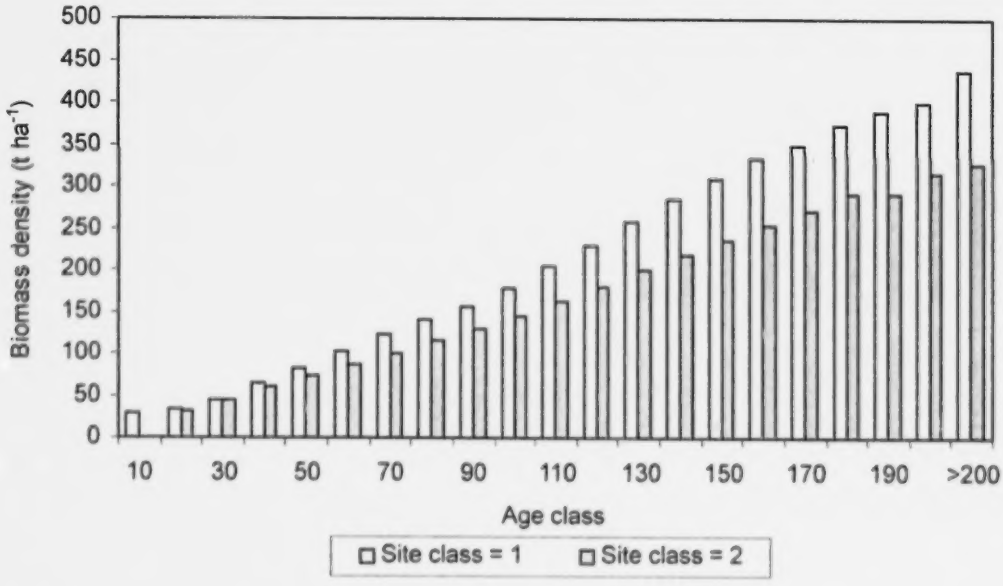

Figure 12. *Distribution of biomass density (including above- and belowground biomass) by age class, simulated for 2000 in the LAMF.*

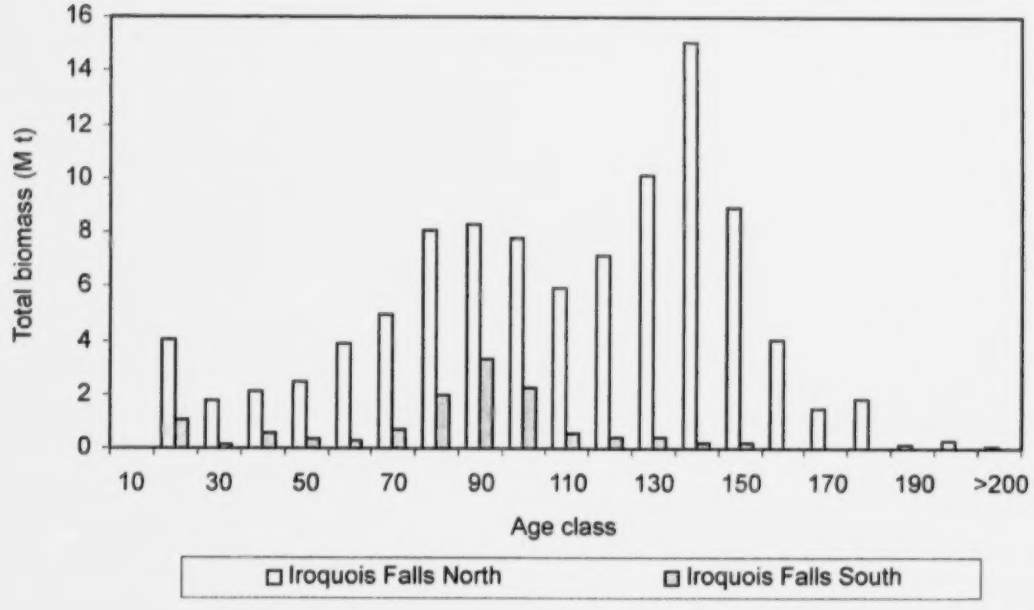

Figure 13. *Total biomass distribution (including above- and belowground biomass) by age class, simulated for 2000 in the LAMF.*

Leaf partitioning affects the proportion of biomass and litterfall directly. In TRIPLEX1.0, the allocation equations adapted from 3-PG (Landsberg and Waring 1997) are expressed as:

$$\eta_r = \frac{0.5}{1 + 2.5\ f_n\ D_e} \quad (4)$$

$$\eta_s = \frac{1 - \eta_r}{1 + P_{fs}} \quad (5)$$

$$\eta_f = 1 - \eta_r - \eta_s \quad (6)$$

where b_r, b_s, and b_f are the allocation ratios for root, stem, and foliage; f_n is nutrient influence depending on site fertility; D_e is the growth limitation by environment; P_{fs} is the allocation factor.

Figure 16 (see solid lines) illustrates an example of the allocation dynamics based on the above equation. All curves are monotone increasing (stem) or decreasing (root and leaf). The problem is, as the forest becomes older, stem increment should decrease and leaves should obtain more of the NPP than before. We revised the allocation equations in this study in order to better simulate some old forest stands in the LAMF. Modifying this allocation was based on two assumptions: (1) that tree growth start to slow down by 200 years of age and (2) that leaves and fine roots make up most of the total biomass. Figure 16 (broken lines) compares these two sets of allocation curves.

Leaf area index (LAI) controls the photosynthetic ability of forest stands. LAI was calculated for each forest stand in the LAMF. Simulated LAI (weighted average) was about 4.7 for black spruce, 1.6 for trembling aspen, and 2.6 for jack pine, respectively. For these species, average LAI was estimated at 3.0 for 2000. Generally, simulated LAI was consistent with LAI (Table 8) measured for boreal forests in Manitoba and Saskatchewan (Newcomer et al. 2000). The distribution of LAI over stand age shows that the highest LAI occurs at approximately 20 years of age in boreal forest stands (Figure 17).

Net primary productivity

The NPP distribution in the LAMF shows that it was lower in Iroquois Falls South and higher in the North (Figure 18). This difference was likely related to soil

Table 7. *Total and average biomass, including above- and belowground, by site class in the LAMF estimated for 2000.*

Tree species	Simulated LAI	Measured[a] LAI (NSA[b])	(SSA[c])
Black spruce	4.7	3.1	5.0
Trembling aspen	1.6	1.4	1.6
Jack pine	2.6	1.9	3.3

[a] Estimated based on data from Newcomer et al. 2000
[b] Northern study area near Thompson, Manitoba (55.7°N, 97.8°W)
[c] Southern study area near Prince Albert, Saskatchewan (53.2°N, 105.7°W)

textures and soil carbon content. However, for stands with similar soil carbon levels, NPP was higher in Iroquois Falls South (Table 8) because stands were younger (with higher growth rates) and mean annual precipitation and temperature were higher. Average NPP was consistent across the LAMF.

In general, NPP increases in younger stands if no intensive disturbance occurred in the previous year. However, increases are not continuous; they depend on the mean annual precipitation and temperature (also see Section 3.4). Comparing annual NPP between stands of different age classes (Figure 19), the old stands (100 – 200 years) had a low NPP in 1995, likely because mean annual precipitation and temperature

Table 8. *Total and average net primary productivity (NPP) calculated for the LAMF in 1990, 1995, and 2000.*

Year	Region	Total NPP (Mt C yr^{-1})	Average NPP (tC $ha^{-1}yr^{-1}$)
1990	North	2.52	3.26
	South	0.40	3.22
	Sum or Average	2.92	3.26
1995	North	2.54	3.28
	South	0.40	3.20
	Sum or Average	2.94	3.28
2000	North	2.58	3.34
	South	0.42	3.26
	Sum or Average	3.00	3.34

Figure 14. *Spatial distribution of site class measured in 1994 for all forest lands (data from LAMF).*

were lower that year. On the other hand, NPP in the younger stands (0 – 100 years) increased gradually every year and in overmature stands (>200 years) it decreased gradually. These results indicate that growth rate has more influence on NPP than climate. Total annual NPP in the LAMF is estimated to be 3.0 Mt C (Table 9).

Relationship between climate and NPP

It is well known that precipitation and temperature affect the spatial patterns and dynamics of NPP at a landscape level. In this study, downscaling was used to show the distribution of precipitation and temperature in the LAMF. Mean annual precipitation in was higher in the southeast than the northwest, with a difference of about 20 mm between Iroquois Falls North and South in 1995. Average temperature was higher in the southwest than the northeast, with a difference of about 0.4°C between Iroquois Falls North and South in 1995. Figure 20 shows mean annual precipitation and temperature in 1990, 1995 and 2000 for the LAMF.

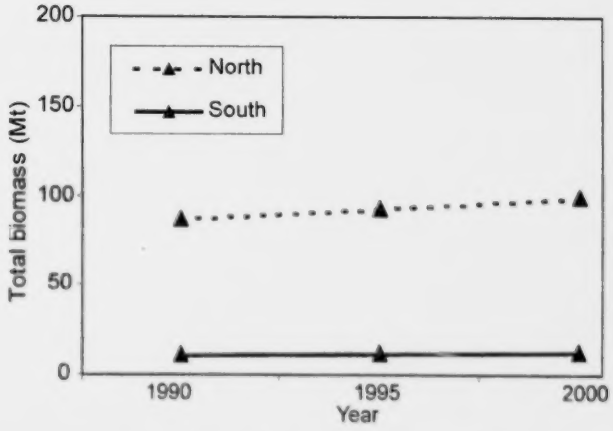

Figure 15. *Estimation of total biomass dynamics (above- plus belowground biomass) in the LAMF from 1990 to 2000.*

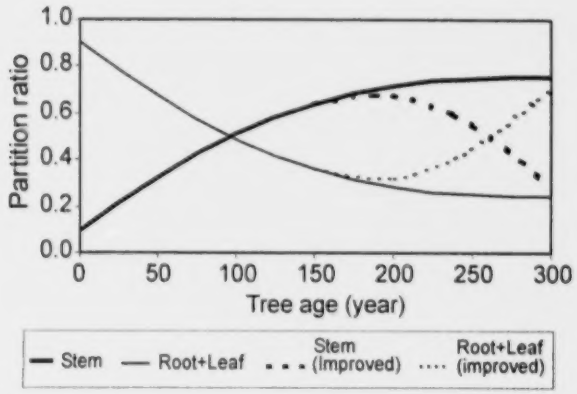

Figure 16. *An example comparing different partition ratios of NPP: (a) allocation used in 3-PG and (b) allocation for TRIPLEX 1.0 used in this study.*

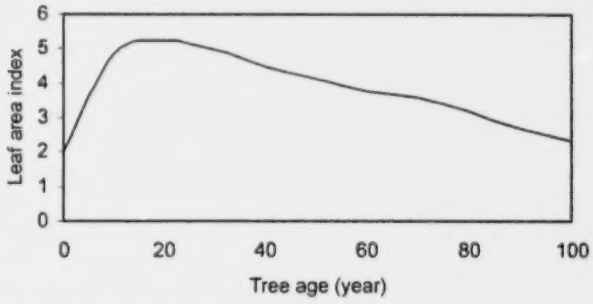

Figure 17. *Distribution of average LAI by tree age for all species, simulated for 2000 in the LAMF.*

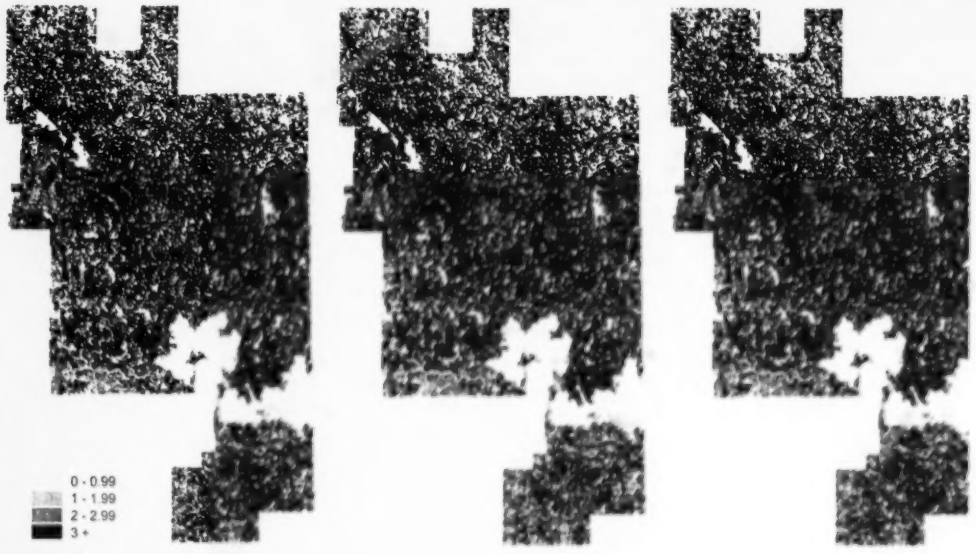

Figure 18. *Estimation of NPP (t C ha^{-1} yr^{-1}) spatial distribution in the LAMF.*

Figure 21 shows the difference in mean annual precipitation and temperature between the two areas in the LAMF during the simulation period (from 1990 to 2000). Both mean annual precipitation and temperature were lowest in 1995, reduced by 70 mm and 0.7°C respectively, compared to 1990. Mean annual precipitation and temperature varied over the 10-year period as did NPP. Total annual NPP was almost identical in 1990 and 1995. It is possible that the lower annual precipitation and temperature in 1990 lowered NPP increment but when precipitation and temperature increased again in 2000, annual NPP also increased.

Soil carbon

The distribution of soil carbon density is shown in Figure 22. Basically, soil carbon content is higher in Iroquois Falls North (Table 10). Total soil carbon in the LAMF is estimated at 83.7 Mt C, and average soil carbon density is about 93.9 t C ha^{-1}. All estimates of soil carbon in this study are limited to forest lands only, and do not include lakes, rivers, and other non-forested areas. Soil carbon includes litter carbon. There are some differences in soil carbon content depending on tree species composition. Comparing sites supporting the dominant tree species in the LAMF, black spruce stands had the highest soil carbon (98 t C ha^{-1}), jack pine stands had the lowest (69 t C ha^{-1}), and trembling aspen stands were intermediate (85 t C ha^{-1}).

The contribution of soil carbon to total ecosystem carbon, which includes aboveground biomass, belowground biomass, detritus, and soil carbon, was estimated and compared between 2 age class groups. On average, soil carbon contributes approximately 60% of total ecosystem carbon for all stands in the LAMF. Younger stands had a higher percentage (around 66%) than older stands (around 51%). There was no significant variation in soil carbon in the LAMF during

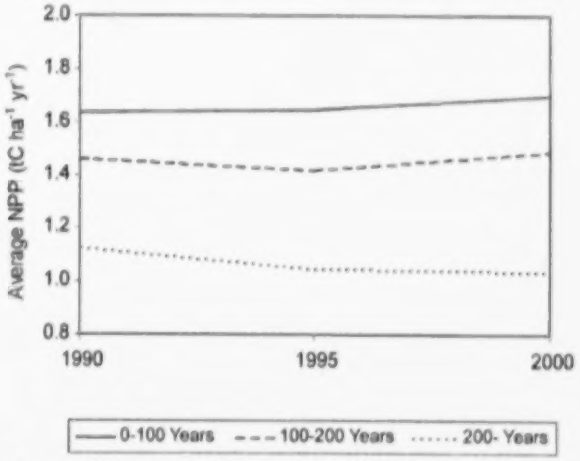

Figure 19. *Annual NPP dynamics for different stand ages for all tree species.*

Table 9. Summary of general properties and carbon stocks of LAMF forest ecosystems in 2000.

	Iroquis Falls North	Iroquis Falls South	LAMF
Ecoregion	3E3	3E6	3E
Average forest age (years)	76	55	72
Forest land area (M ha)	0.74	0.16	0.9
Biomass carbon (Mt C)	49.2	6.3	55.5
Litter and soil carbon (Mt C)	75.8	7.9	83.7
Biomass carbon density (t C ha^{-1})	61.9	51.8	60.4
Litter and soil carbon density (t C ha^{-1})	98.4	66.3	93.9

the period from 1990 to 2000. Soil carbon was stable in the absence of intensive disturbances (i.e., neither fire nor large harvest areas were evident during the simulation period).

For the LAMF region, forest ecosystem carbon (including vegetation, detritus, and soil) density was estimated at 154.4 t C ha^{-1} with 60% of the carbon in soil (see Table 10). Average total soil carbon (including litterfall carbon) was twice that of aboveground biomass carbon (46.0 t C ha^{-1} converted from Table 5). This means that the proportion of soil carbon and aboveground biomass carbon agrees with our analysis of the field data (the ratio is about 2:1) from boreal ecosystems (Newcomer et al. 2000) and other available forest databases (CLBRR 1993, Siltanen et al. 1997, ORNL 2000). This ratio was also reported by Peng et al. (1998) and Price et al. (1999). Generally, litterfall return carbon from biomass carbon stocks to soils and different stand age and tree species determine this flux.

Unfortunately, we do not have point by point field measurements of soil carbon for the entire LAMF, so we have to use the existing national soil carbon database as a general reference to verify our model simulations. Results show that soil carbon density ranged from 60 to 120 t C ha^{-1} in 63% of the LAMF area in 2000 (average=93.9 t C ha^{-1} , SD=28.3). Comparing our estimates of average soil carbon with other soil databases, the range (primarily 60-120 t C ha^{-1}) of average soil carbon density simulated by TRIPLEX1.0 is acceptable. For comparison, Siltanen et al.'s (1997) results showed that soil carbon density was about 98 t C ha^{-1} (including mineral and organic horizons) averaged over 170 soil samples in the eastern boreal forest region of Ontario, which is slightly higher than our simulated soil carbon (e.g., 93.9 t C ha^{-1}, see Table 10) for the LAMF.

Table 10. Carbon (C) dynamics and balance in the LAMF forest ecosystem, simulated for 1990 – 2000.

Variable	1990	1995	2000	Average
Total C stock	132.4	135.8	139.2	-
Biomass C stock	48.3	52.0	55.5	-
Soil and litter C stock	84.1	83.8	83.7	-
NPP	2.92	2.94	3.00	2.96
Harvesting	0.13	0.14	0.12	0.13
C release	0.94	0.95	0.96	0.95
Net C balance	1.98	1.99	2.04	2.01

Net carbon balance

General forest carbon-related features of the LAMF in 2000 are presented in Table 10, and the net carbon balance from 1990 to 2000, which was about 2 Mt C yr^{-1} without the harvest removal, is provided in Table 11. During the estimation period, NPP was greater than carbon release.

Biomass C stocks were estimated to be 39.9% of total carbon stock in the LAMF ecosystem (Figure 23). Aboveground biomass was 76.0% of total biomass carbon. The carbon content of harvesting was converted from local LAMF data. Actual harvest volume was around 550,000 m^3 (Griffin 2001b). Our recent study (Zhou et al. 2004) reported that average wood carbon density in the boreal forest region is 0.22 t C m^{-3} for boreal forests. NBP was estimated at about 1.9 Mt C yr^{-1}, which indicates a net carbon gain after harvesting in 2000.

Overall carbon budgets for 1990, 1995 and 2000 were also estimated (Table 10). Total net C sequestration through forest growth (NPP) was estimated at 3 Mt C yr^{-1} in the 1990s. Total biomass carbon stock was 55.5 Mt C in 2000. This study shows that LAMF forest ecosystems were acting as a carbon sink in the 1990s (around 2 Mt C yr^{-1} from 1990 to 2000), even though Ontario's forest ecosystems acted as an overall source

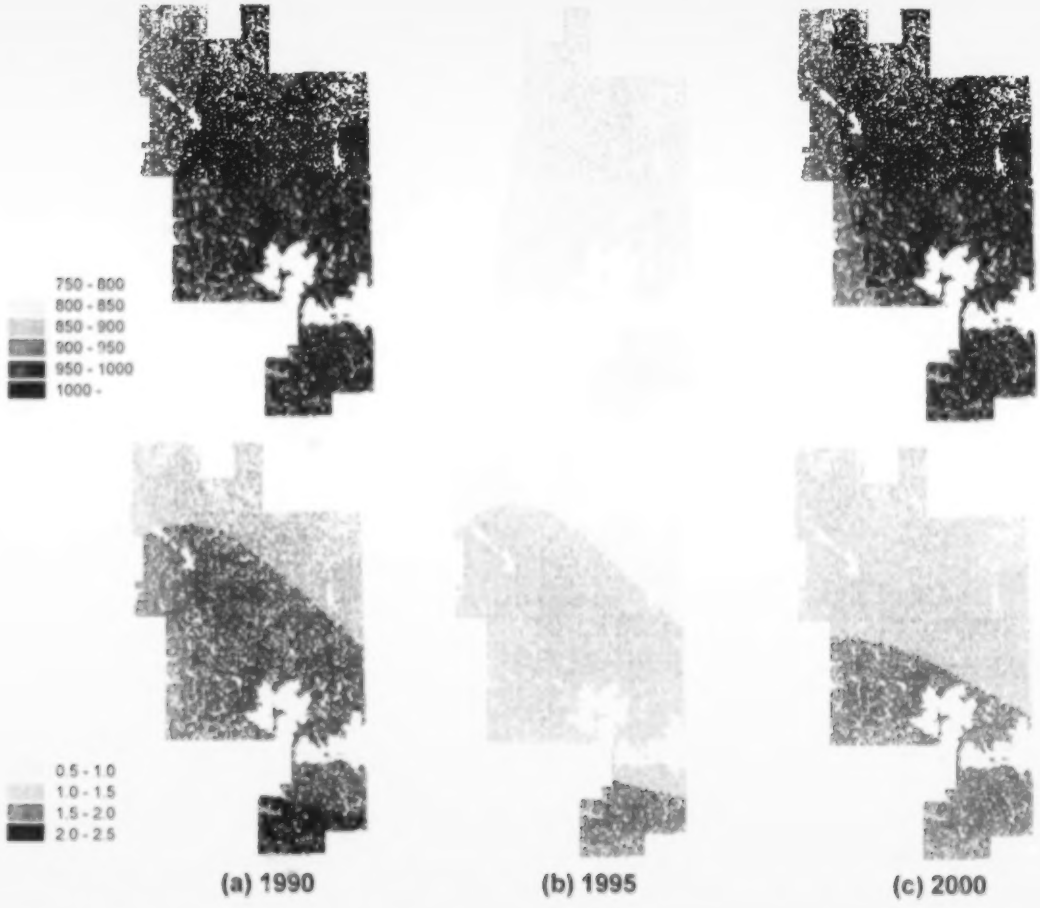

Figure 20. *Spatial distribution of average temperature (°C) and annual precipitation (mm) in the LAMF from 1990 to 2000.*

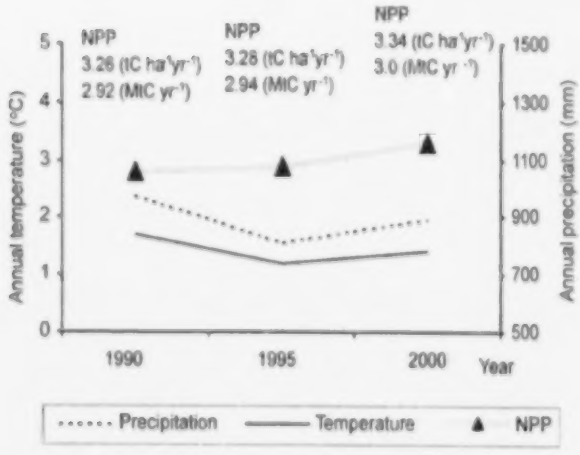

Figure 21. *Dynamics of annual NPP simulated for the LAMF.*

(-31 Mt C estimated in 1990) (Peng et al. 2000). This is likely because of the younger average age of the stands on the LAMF (average of 72 years), which resulted in higher productivity as shown by the relation between stand age and NPP (Figure 19). Another possible reason is that there were very few disturbances (e.g., harvesting, fire) that occurred in the LAMF during the 1990s.

Biomass and soil carbon stocks were estimated before harvesting (Table 10). However, harvesting did not affect net carbon balance significantly because allowable harvest in the LAMF is limited from 1990 to 2015. Allowable harvest is set at approximately 750,000 m^3, which amounts to 0.16 Mt C annually. Actual harvested volume was even lower than the allowable harvest. This study does not include the

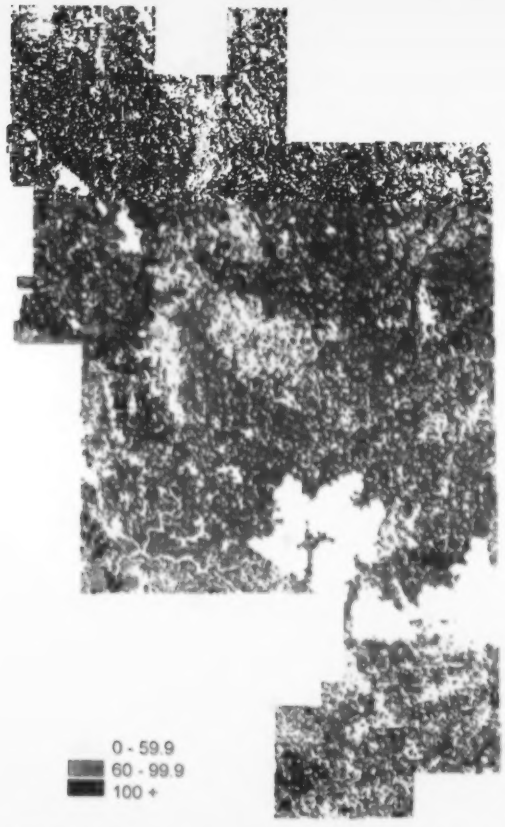

Figure 22. *The distribution of soil and litter carbon density (t C ha^{-1}) simulated for 2000 in the LAMF.*

effect of forest fire due to the lack of a fire module. However, forest fires are not frequent in the LAMF. Burns covered only 0.38% of the area of the LAMF in the 1990s, indicating that carbon released from the ecosystem by forest fire was very limited and had virtually no effect on the overall carbon balance of the LAMF ecosystems.

Future Research

The LAMF is one of 11 Canadian model forests and plays an important role in the monitoring of forest sustainability at local levels. The carbon cycle in boreal forest regions is becoming an increasingly important topic in understanding both local and global climate change and the ongoing negotiation of international agreements related to the Kyoto Protocol. In this study, we demonstrated one application of the TRIPLEX1.0 model to investigate biomass dynamics, NPP increment, soil carbon, and net carbon balance in the LAMF area. This information will be useful to local forest managers for developing ecological and scientifically sound indicators for monitoring the sustainability of forest ecosystems, and making more informed management decisions.

However, the results of this study were limited not only by the limited availability of field data but also by the current version of the TRIPLEX model. To

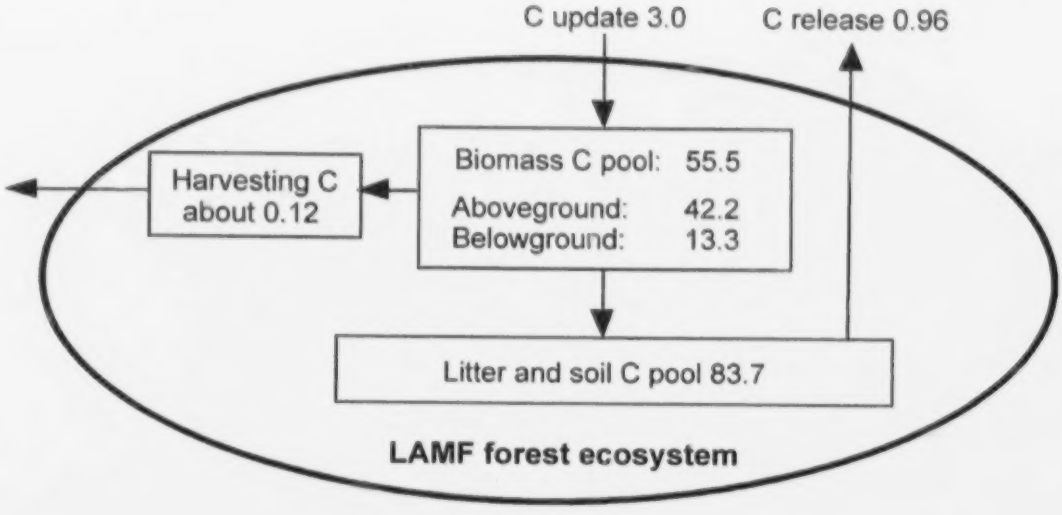

Figure 23. *Carbon balance (Mt C) of the LAMF forest ecosystems in 2000 (net C balance=2.04).*

predict the effects of future climate change, CO_2 concentrations need to be considered and the impacts of ecosystem disturbances and forest management regimes should be taken into account. These disturbance processes will be incorporated into the next version of the TRIPLEX model at which time the results of this study should be reevaluated. In addition, since the TRIPLEX1.0 model was a monthly time step, simulation of daily carbon flux is limited. This will need to be improved through ongoing projects, for example in cooperation with the Fluxnet-Canada network in future.

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Appendix

Table 1. Permanent sample plots (PSP) located in the LAMF that were used in this study. Data were updated in 1994.

Code	Longitude	Latitude	Species[a] (dominant)	Average age (year)	Soil texture
COC9401	-80.60	49.04	Black spruce	64	Clay
COC9402	-80.47	49.44	Black spruce	84	Clay
COC9403	-80.46	49.41	Black spruce	116	Fine sand
COC9404	-80.75	49.60	Black spruce	98	Clay
COC9405	-80.46	49.45	Black spruce	50	Clay
COC9406	-80.64	49.04	Black spruce	64	Clay & medium sand
COC9407	-80.69	49.22	Black spruce	75	Clay
COC9408	-80.67	48.74	Trembling aspen	85	Clay
COC9409	-80.71	48.77	Glossy buckthorn	75	Clay
COC9410	-80.70	48.79	Black spruce	53	Clay
COC9411	-80.62	49.02	Black spruce	92	Clay & medium sand
COC9412	-80.63	48.97	Black spruce	66	Clay
COC9416	-80.64	48.73	Glossy buckthorn	69	Clay
COC9418	-80.64	49.06	Black spruce	48	Clay & medium sand
COC9419	-80.66	49.12	Black spruce	50	Clay & medium sand
COC9420	-80.68	48.86	Black spruce	92	Clay
COC9421	-80.29	49.47	Black spruce	66	Clay
COC9422	-80.68	48.85	Black spruce	53	Clay
COC9423	-80.62	48.99	Jack pine	36	Clay & medium sand
COC9424	-80.62	49.04	Black spruce	55	Clay
COC9425	-80.44	48.94	Trembling aspen	58	Clay
COC9426	-80.40	48.99	White birch	27	Clay
COC9427	-80.55	49.04	Black spruce	59	Clay
COC9428	-80.42	49.06	Black spruce	51	Clay
COC9429	-80.68	49.16	Balsam fir	38	Clay
COC9430	-80.67	49.19	Black spruce	76	Clay
COC9431	-80.53	49.04	Black spruce	69	Clay
COC9432	-80.64	48.95	Black spruce	119	Clay
COC9433	-80.48	49.06	Trembling aspen	67	Clay & medium sand
COC9434	-80.44	49.20	Black spruce	20	Clay
COC9435	-80.45	49.41	Black spruce	20	Fine sand
IFF9301	-80.65	49.08	Jack pine	42	Clay
IFF9302	-80.49	49.16	Black spruce	91	Clay
IFF9303	-80.50	49.14	Black spruce	43	Clay
IFF9304	-80.67	48.75	Trembling aspen	51	Clay
IFF9306	-80.49	49.17	Black spruce	90	Clay
IFF9307	-80.33	48.72	Trembling aspen	50	Clay
IFF9308	-80.51	49.37	Jack pine	12	Clay
IFF9309	-80.45	49.36	Black spruce	9	Fine sand
IFF9310	-80.39	49.38	Jack pine	12	Medium sand
KLK9201	-79.93	48.28	Jack pine	50	Fine sand
KLK9209	-80.05	48.36	Black spruce	20	Fine sand
KLK9301	-79.93	48.28	Jack pine	50	Fine sand
KLK9404	-79.91	48.36	Black spruce	66	Fine sand
KLK9418	-79.91	48.36	Balsam fir	71	Fine sand
KLK9419	-79.92	48.35	Black spruce	96	Fine sand
KLK9424	-80.20	48.29	Trembling aspen	90	Clay
KLK9425	-80.20	48.30	Black spruce	90	Clay
KLK9445	-79.77	48.49	Jack pine	55	Fine sand

[a] black spruce (*Picea mariana*), jack pine (*Pinus banksiana*), trembling aspen (*Populus tremuloides*), white birch (*Betula papyrifera*), glossy buckthorn (*Rhamnus frangula*), balsam fir (*Abies balsamea*).

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